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Evaluating management strategies for eastern Bering Sea walleye pollock (*Theragra chalcogramma*) in a changing environment

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The impacts of climate change on fish and fisheries is expected to increase the demand for more accurate stock projections and harvest strategies that are robust to shifting production regimes. To address these concerns, we evaluate the performance of fishery management control rules for eastern Bering Sea walleye pollock stock under climate change. We compared the *status quo* policy with six alternative management strategies under two types of recruitment pattern simulations: one that follows temperature-induced trends and the other that follows a stationary recruitment pattern similar to historical observations. A subset of 82 Intergovernmental Panel on Climate Change climate models provided temperature inputs from which an additional 100 stochastic simulated recruitments were generated to obtain the same overall recruitment variability as observed for the stationary recruitment simulations. Results indicate that *status quo* management with static reference points and current ecosystem considerations will result in much lower average catches and an increased likelihood of fishery closures, should reduced recruitment because of warming conditions hold. Alternative reference point calculations and control rules have similar performance under stationary recruitment relative to *status quo*, but may offer significant gains under the changing environmental conditions.

Keywords: climate models, eastern Bering Sea walleye pollock, fisheries management, harvest strategies.

Introduction

The task of applying the best available information to fisheries management advice involves a number of challenges. Among these challenges is estimating how environmental interactions affect stock dynamics and communicating uncertainty in a way that is useful for management decisions (Basson, 1999; A'mar *et al.*, 2009; Holt and Punt, 2009; Perry *et al.*, 2010; Prager and Shertzer, 2010). These issues are of particular concern for the Bering Sea walleye pollock (*Theragra chalcogramma*; hereafter referred to as pollock) stock (Wespestad *et al.*, 2000; Ianelli, 2005; Jurado-Molina *et al.*, 2005; Mueter *et al.*, 2007, 2011).

Eastern Bering Sea (EBS) pollock fishery catches have averaged 1.2 million tonnes annually since 1980 and represent the largest fishery in the United States by volume (NMFS, 2009a). Their management has gradually transitioned from foreign and joint venture to a fully domestic fishery under management plans established by the North Pacific Fishery Management Council (NPFMC; Witherall *et al.*, 2000; Livingston *et al.*, 2011). The management guidelines have evolved into a set of rules that are reviewed during each annual assessment cycle for near-term management guidance. Periodically, the overarching long-term management strategies are re-evaluated within the context of single-species assessments and an array of external factors affecting fishery impacts (e.g. total removals, bycatch, and market constraints; NMFS, 2004, 2009b). Additionally, there is a 2.0-million tonne optimum yield (OY), which sets the upper limit of the total annual groundfish extraction from the EBS.

As knowledge of the functional relationship between climate variability and fish production improves, analysts are beginning to account explicitly for environmental trends because of climate change in Alaska groundfish fisheries (Hollowed *et al.*, 2009). Mueter *et al.* (2011) evaluate hypotheses on processes linking climate variability to EBS pollock recruitment. They provide evidence that summer ocean temperature may serve as a proxy for factors affecting pollock recruitment. Schnute *et al.* (2007) challenged the scientific community to design tools to evaluate fishery management strategies. Here, we present an approach to evaluating a hypothetical relationship to project the consequences of climate change (acknowledging other sources of variability) and compare that with a scenario based on the stationary historical patterns of recruitment.

Methods

The Intergovernmental Panel on Climate Change (IPCC) scenarios (IPCC, 2007) were downscaled to the EBS ecosystem. Following Wang *et al.* (2010), retrospective studies were conducted to identify models that perform poorly for the EBS region, and these models were excluded from consideration. This involved evaluating the fit to the spatial pattern, temporal scale, and magnitude of variance of the sea surface temperature (SST). According to the methodology described by Mueter *et al.* (2011), the selected models resulted in 82 different time-series of future EBS SSTs that range from 7 to 11°C (Figure 1). Projections from these models are treated as plausible future temperature patterns.

Management scenarios are derived based on the professional judgement of the authors and informal interviews with members of the fishing community. Tompkins *et al.* (2008) highlights the importance of engaging stakeholders when developing planning scenarios for responses to climate change. Informal interviews were done over the course of one year to gain insights of expected responses to anticipated changes in the economy (shifting fuel prices, worldwide demand for whitefish, and catch efficiency) and societal preferences regarding conservation. A qualitative assessment of the impacts of changes was conducted to identify seven management scenarios described in Table 1.

Pollock stock status was projected with a model used for groundfish stocks in US waters off Alaska. This model was designed to implement the Fishery Management Plan as modified under Amendment 56 (Anon., 1999). Inputs include estimated begin-year numbers-at-age in the terminal year (here 2010), age-specific schedules for selectivity, maturity, natural mortality, and mean weights for each fishery and for the population at time of spawning. The time-series of simulated future recruits were computed using two different methods: (i) from predictions of recruitment based on climate (SSTs) via the functional relationship established by Mueter *et al.* (2011; Figure 2), and (ii) from the historical patterns of recruitment (i.e. with mean and variance estimated for simulations via the inverse Gaussian distribution; Figure 3).

For the *status quo* policy (as applied here), the first step to determining the catch level in year t required determining F_t, the fishing mortality as a function of spawning biomass (B_t):

$$\begin{aligned}
&\text{Stock status}: \ B_t/B_{\text{msy}} > 1\\
&\quad F_t = F_{\text{msy}},\\
&\text{Stock status}: \ 0.05 < B_t/B_{\text{msy}} \le 1\\
&\quad F_t = F_{\text{msy}}(B_t/B_{\text{msy}} - 0.05)(1-0.05)^{-1},\\
&\text{Stock status}: \ B_t/B_{\text{msy}} < 0.05\\
&\quad F_t = 0.0,
\end{aligned}$$

where B_{msy} is a reference biomass for pollock where the unfished spawning contribution is reduced to 27% of expectation per

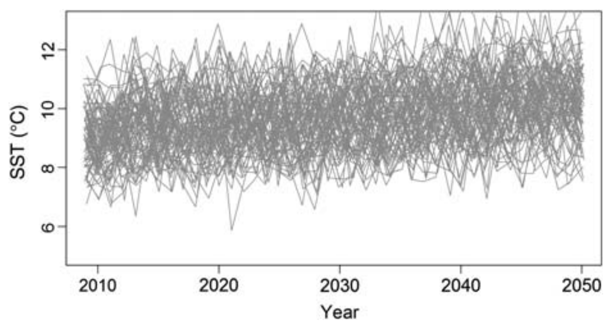

Figure 1. Time-series of future SSTs over the EBS based on the selected 82 climate change models (from Mueter *et al.*, 2011).

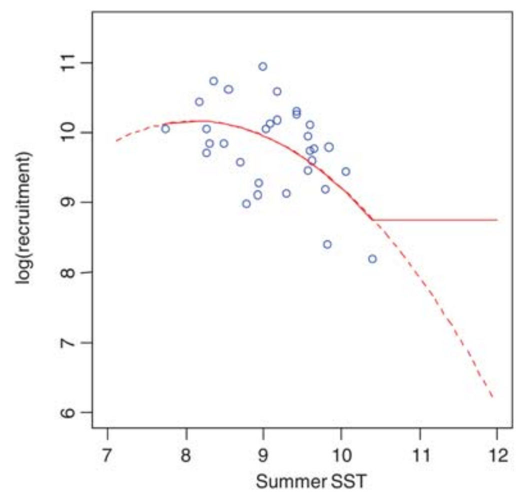

Figure 2. Summer temperature effect used to model the relationship between climate change models and pollock recruitment (from Mueter *et al.*, 2011). The dashed line represents the estimated functional form and the solid line the assumption used for the simulations.

Table 1. Comparisons of alternative management strategies evaluated under the two future recruitment scenarios.

Policy abbreviation	Name	Effect of modification
Status quo	*Status quo*	–
Adj *B*47%	Adjust fishing mortality at stock sizes $>B_{\text{msy}}$	Begin ramping fishing mortality downwards as biomass drops below 1.143 B_{msy}
20-year B_0%	Compute B_0 based on recent 20-year mean recruitment	$B_{20\%}$ changes dynamically with recent 20-year period (changing carrying capacity affects Steller sea lion rule)
wtd B_0%	Compute B_0 weighted by recent recruitment to spawning[a]	$B_{20\%}$ changes dynamically with recent recruitment and expected contribution to spawning biomass (changing carrying capacity affects Steller sea lion rule)
Low cap	Low cap	Limit the maximum level of pollock removals to 1.3 million tonnes
High cap	No cap	Allow catches to be unconstrained during the periods of high biomass (set TAC = ABC and ignore 2 million tonne catch limit)
Const *F*	Constant fishing mortality	As in policy above, but also ignore any adjustments in fishing mortality rates as stock drops below target and $B_{20\%}$ levels

[a]Computed as spawning biomass per recruit multiplied by $\bar{R}_t = \sum_{a=1}^{25} \phi_a w_a N_{t-a+1,1} e^{-\sum_{i=1}^{a-1} M_i} \left(\sum_{a=1}^{25} \phi_a w_a e^{-\sum_{i=1}^{a-1} M_i} \right)^{-1}$ (after A'mar *et al.*, 2009).

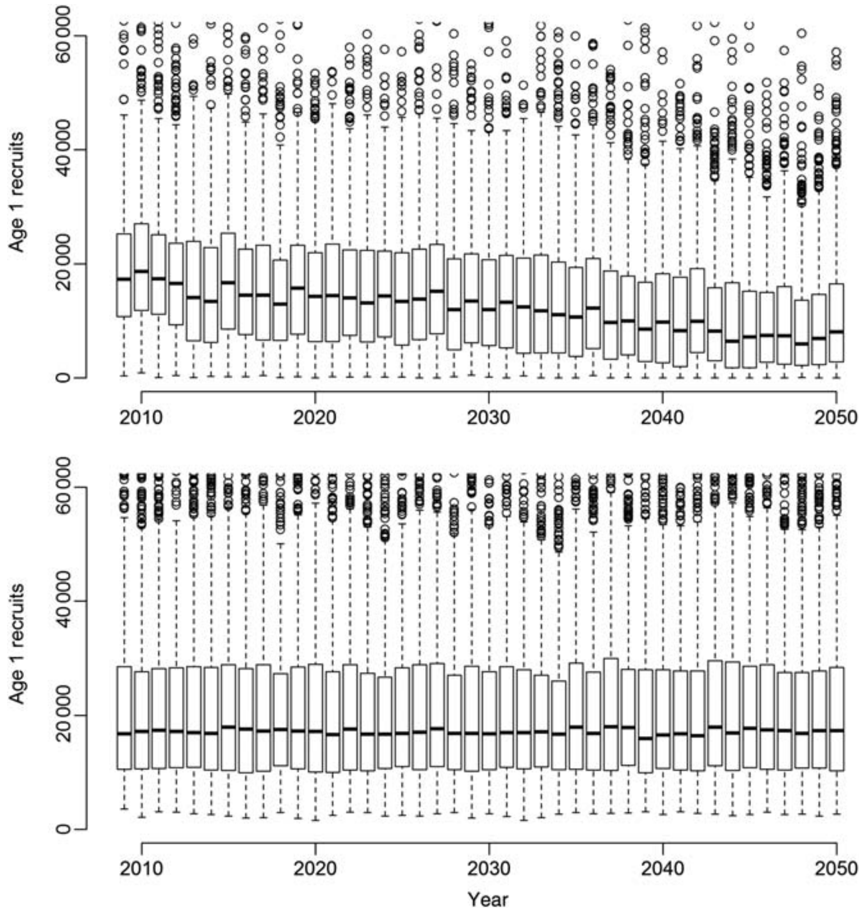

Figure 3. Simulated pollock recruitments as projected using the climate relationship (top panel for the 82 climate models selected, with 10 Monte Carlo simulations for each year and model) and assuming stationary future recruitment levels (bottom panel; also for the 820 simulations evaluated).

recruit (Ianelli *et al.*, 2009). Catch in mass by year was determined from the Baranov catch equation:

$$C_t = \sum_{a=1}^{15} w_a N_{a,t} \frac{F_{a,t}}{Z_{a,t}} (1 - e^{-Z_{a,t}}),$$

where $N_{a,t}$ is the begin-year numbers-at-age a, in year t, w_a the mean body-mass-at-age for pollock (in the fishery), and the age-specific fishing mortality follows a separable form ($F_{a,t} = s_a F_t$) and $Z_{a,t} = M_a + F_{a,t}$, with s_a the selectivity-at-age and M_a the assumed age-specific natural mortality age (Ianelli *et al.*, 2009). The next step was to constrain the fishing mortality such that it must result in catches of no more than 1.5 million t year^{-1}. This level approximates the adjustment in TAC when the sum of other groundfish acceptable biological catches (ABCs) exceeds the OY of 2 million tonnes. For example, in 2004, the pollock ABC was 2.56 million tonnes and the TAC was 1.492 million tonnes.

Numbers-at-age in future years are given as:

$$\begin{aligned} N_{a,t} &= N_{a-1,t-1} e^{-Z_{a,t}} \quad 1 < a < 15 \\ N_{15,t} &= N_{14,t-1} e^{-Z_{14,t}} + N_{15,t-1} e^{-Z_{15,t}} \\ N_{1,t} &= \bar{R}_t e^{\varepsilon_{t,E}} \quad \varepsilon_t \sim N(0, \sigma_E^2), \end{aligned}$$

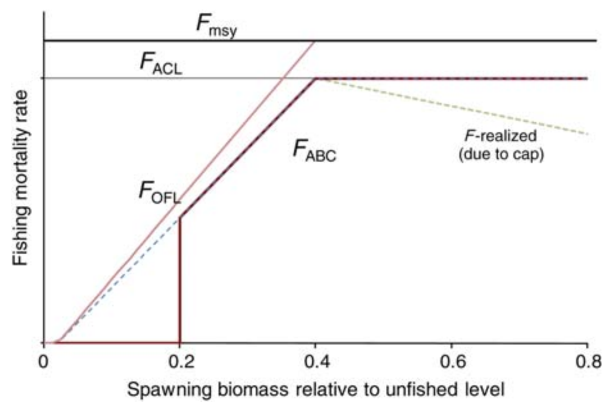

Figure 4. Schematic of harvest control rule currently affecting ABC or annual catch limit (ACL) for Alaska groundfish species like pollock (thick line). Note that this schematic indicates that B_{msy} is 40% of the unfished expected spawning biomass.

where $\bar{R}_t = e^{9.7886 - 1.763\,\mathrm{SST} - 0.6626\,\mathrm{SST}^2}$ for the scenario where the climate model effects (Mueter *et al.*, 2011) are included and otherwise $\bar{R}_t$ is set as constant over time and equal to the historical level of recruitment as estimated in Ianelli *et al.* (2009). The subscript E designates whether or not the climate effects are included and the variance term of recruitment was set so that the total recruitment variability equalled 0.67^2 for both recruitment generation scenarios.

Spawning biomass is tracked by projecting numbers-at-age from begin-year abundances and applying the age-specific maturity, ϕ_a, for female pollock:

$$B_t = \sum_{a=1}^{15} \phi_a w_a N_{a,t} e^{-0.25 Z_{a,t}},$$

assuming peak spawning occurs on 1 April. Finally, should the spawning biomass (B_t) fall below 20% of unfished stock size, as part of the Steller sea lion forage management measure, the directed fishery for pollock must be curtailed. Schematically, the effect of combining the species-specific control rule with externalities described for Steller sea lion considerations and overall ecosystem removals (the 2 million tonne cap) illustrates how fishing mortality is constrained in Figure 4.

The alternative management strategies are described as deviations from the *status quo* in Table 1. Briefly, they include the following policies: "Adj $B47\%$" adjusts the fishing mortality downwards as biomass approaches the "target" size (as opposed to after the stock is below that level; Dorn *et al.*, 2005); "20-year $B_0\%$" and "wtd $B_0\%$" are two policies that allow for gradual changes in carrying capacity such that the unfished stock size can change (and consequently the absolute level of $B_{20\%}$ for Steller sea lion management); "low cap" changes the upper limit of pollock TAC from 1.5 to 1.3 million tonnes; "high cap" removes the upper limit on catch (because of OY constraint) completely; and "const F" is a policy that sets the fishing mortality rate to be constant for all levels of stock size.

Table 2. Comparisons of alternative management strategies evaluated under the two future recruitment scenarios.

Indicator	Weight
Stock status	
Spawning stock level	2.0
Number of years stock falls below $B_{20\%}$	1.0
Fishery	
Catch variability	0.5
Interannual catch variability	1.0
Mean catch	1.5
Number of years that fishery closes	3.0

Table 3. Qualitative assessment of economic and societal changes in 2050.

Factor	Outcome
Competition from whitefish aquaculture	Increase
Fuel price	Increase
Demand for whitefish from population increase	Increase
Conservation concerns to restrict resource use	No change
Uncertainty in stock assessment	Decrease
Acceptance of climate change impacts on carrying capacity	Increase

Policy evaluation

For each harvest strategy, a variety of fishery indicators was computed for comparison. These included the simulation distributions of spawning-stock biomass, the number of years where the spawning biomass falls below $B_{20\%}$, mean catch, the number of years that the fishery would be closed, the overall catch variability, and the between-year catch variability. These statistics are compared for alternative policies and provide a way to evaluate risks, trade-offs, and the robustness of these harvest strategies. Results from these Monte Carlo simulations are presented graphically for the different policies and recruitment scenarios over time and summarized using violin plots—a modified type of box plot that provides improved insight on multimodal results (Hintze and Nelson, 1998). It can also be informative to provide a scoring system, so that indicators can be aggregated and policies more easily compared. Here, the indicators can be categorized as being

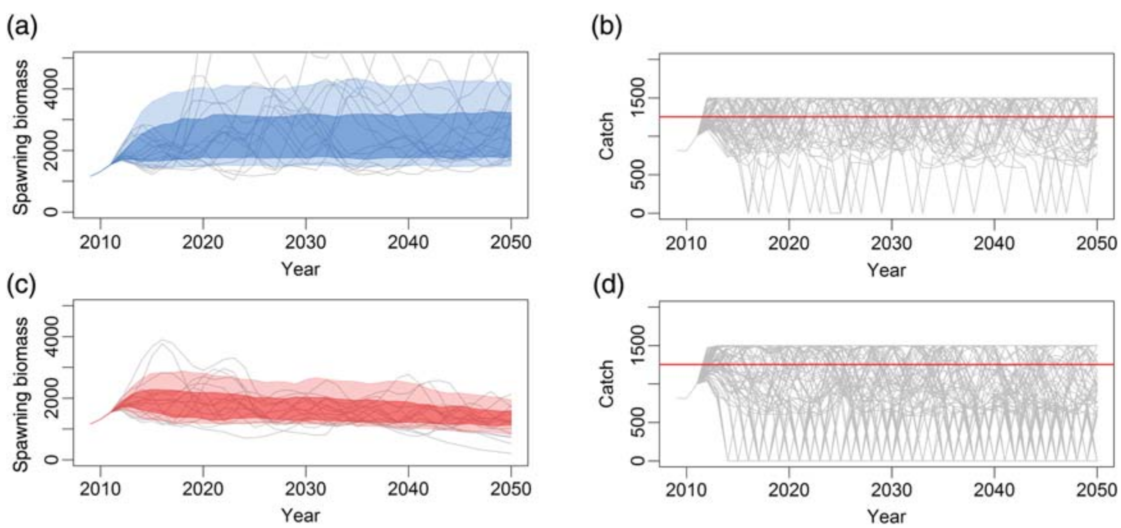

Figure 5. Projected pollock spawning biomass and catch under the current harvest control rule with stationary environmental conditions (a and b) and under the 82 IPCC models selected for EBS SSTs (c and d). For the spawning biomass figures (a and c), the shaded swathes represent 25th and 75th percentiles (dark shade) and 10th and 90th percentiles (light shade). In the catch figures (b and d), the individual lines represent results from a single Monte Carlo trial and the straight horizontal line represents the historical average catch (1964–2009).

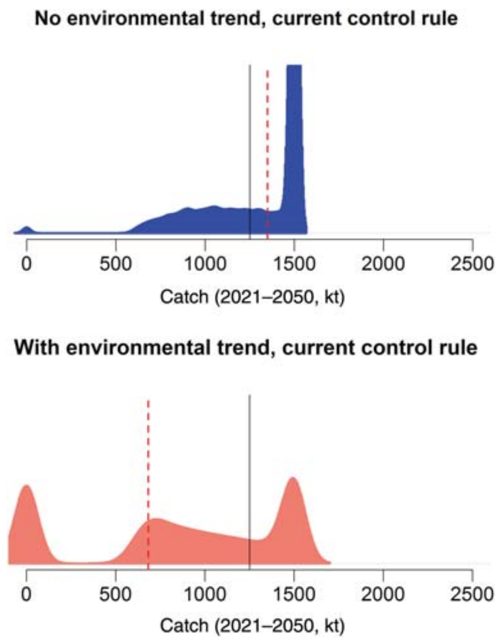

Figure 6. Relative frequency (kernel-smoothed) of individual Monte Carlo simulations of pollock catch under the current harvest control rule with stationary environmental conditions (top panel) and under the 82 IPCC models selected for EBS SSTs (bottom panel). The vertical solid line represents historical mean yields (1964–2009) and the dashed line the mean value from the simulations.

related to either stock size or fishery yield. To illustrate how policies can be compared, an example application with subjectively specified weights was given (Table 2). Scores were computed for each policy by multiplying their rank (such that a higher value indicated a better performance) by the weights for each of the indicators, summing the values, then normalizing over all policies so the scores average 1.0.

Results

The qualitative assessment of the expected direction of change in economic and societal factors is summarized in Table 3. Competing economic factors are expected to make the net prediction for economic conditions neutral to somewhat positive as market competition from aquaculture and increasing fuel and other inputs costs is offset by the increased demand for whitefish, because of population growth and economic development. These factors are likely to continue to provide an incentive for at-sea fisheries, even under scenarios of very high fuel costs. Conservation concerns are unlikely to increase because the stocks in the Bering Sea are managed conservatively. However, given population fluctuations generally, it is expected that new conservation concerns will arise and will have to be addressed. Should stock assessment uncertainty decrease substantially in future, managers may be inclined to relax the 2 million tonne overall groundfish limit. For pollock in particular, improved precision would reduce the buffer between the ABC (the upper limit of the TAC) and the

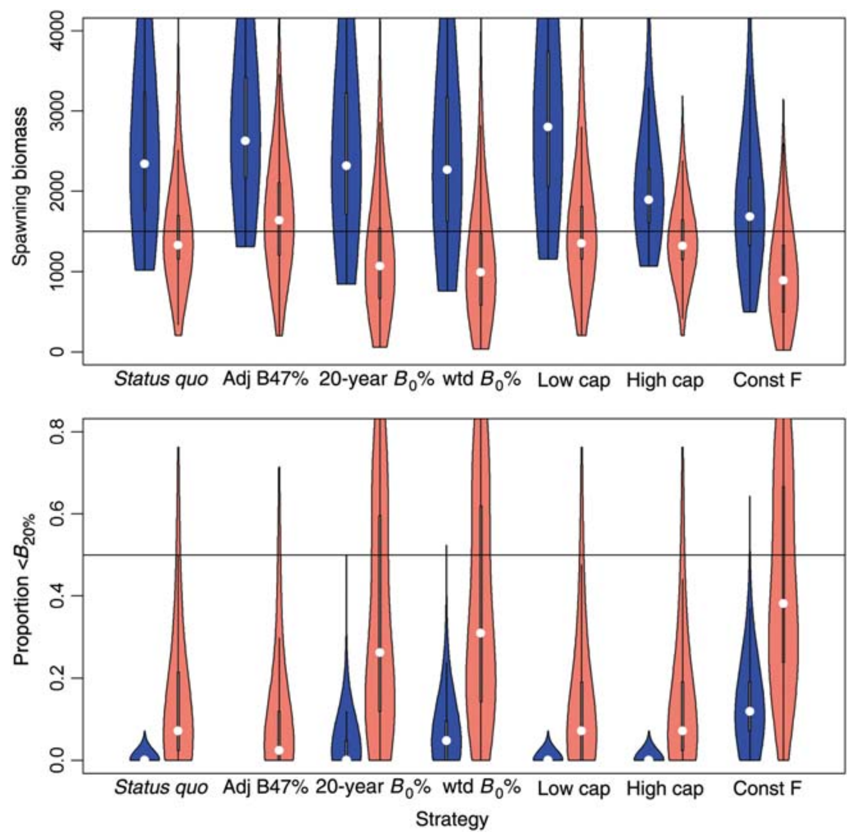

Figure 7. Relative frequency of individual Monte Carlo simulations of 2010–2050 spawning biomass (top panel) and proportion of times that spawning biomass fell below $B_{20\%}$ (bottom panel) under alternative harvest strategies with stationary environmental conditions (densities on left) and under the 82 IPCC models selected for EBS SSTs (densities on right). Horizontal lines are for reference relative to the 2009 value (top panel) and 50th percentile (bottom panel).

overfishing level (set to equal the projected yield at F_{msy}). This buffer is currently in place to account for uncertainty in F_{msy} estimates.

For simulated projections of the current control rule, the time-series of spawning biomass and catches varied substantially, but the impact of the climate change scenario indicates an overall decline in pollock biomass and lower catch levels (Figure 5). Comparing the relative frequency of simulated catches with the current management policy with environmental effects reveals that future catch is likely to be much lower than historical levels and simulations assuming stationary environmental conditions (Figure 6).

Comparing the statistics over the seven different policies with and without stationary recruitment provides the ability to evaluate whether alternative policies can consistently outperform the *status quo* policy. For example, the distribution of simulated spawning biomass and the proportion of simulations that dropped below the $B_{20\%}$ level for the climate change simulations failed to improve substantively over the *status quo* policy (Figure 7). However, alternative harvest strategies that allowed for changes in carrying capacity (by changing the period over which B_0 is calculated—catch policies "20-year B_0%" and "wtd B_0%") provided slightly better catch levels and lower variability (Figure 8).

To examine the indicators in an integrated way, the example factor weights (Table 3) were applied. Because the indicators could be categorized as either a measure of stock condition or fishery production indicators, comparing these with the combined

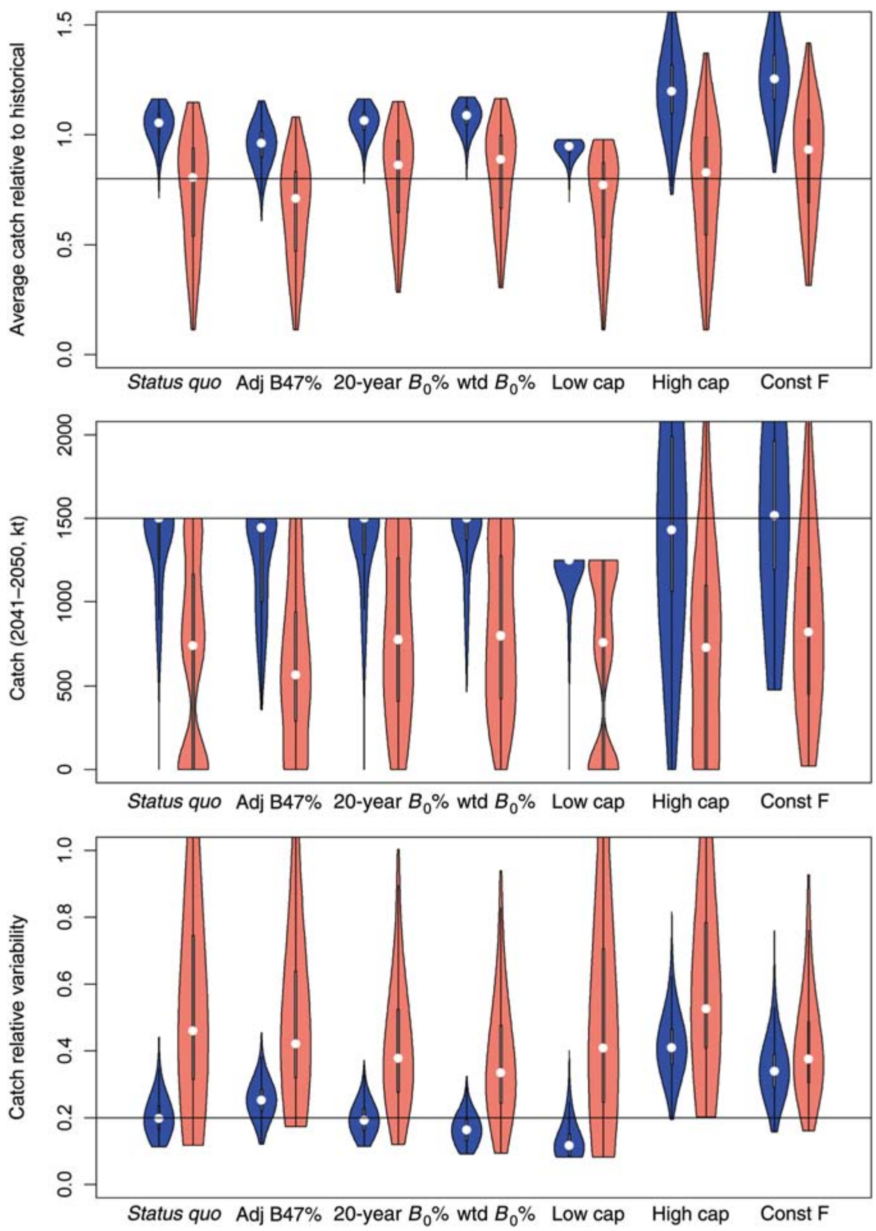

Figure 8. Relative frequency of individual Monte Carlo simulations of 2010–2050 average catch (top panel), catch in the last 10 years of the simulation (middle panel) and catch variability (bottom panel) under alternative harvest strategies with stationary environmental conditions (densities on left) and under the 82 IPCC models selected for EBS SSTs (densities on right). Horizontal lines are simply for reference to facilitate comparisons.

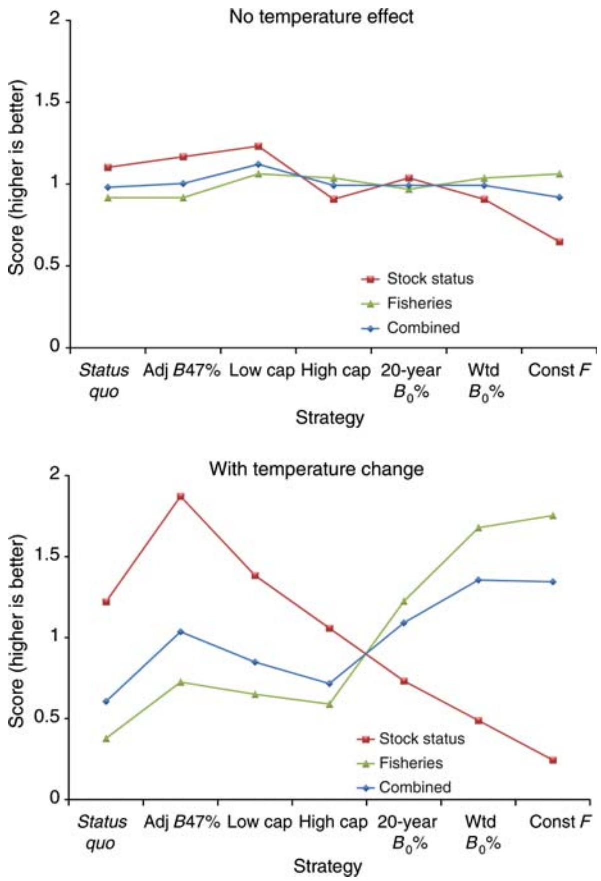

Figure 9. Normalized scores by "stock status" and "fisheries" categories and combined for different policies assuming stationary pollock recruitment pattern (top panel) and for simulations with recruitment that is affected by temperature (bottom panel).

scores is revealing. For the projections that assumed climate change and a temperature effect on recruitment, some strategies outperformed the *status quo* compared with the stationary recruitment assumption (Figure 9). However, for these example weightings, under no temperature effect, the benefits of changing the harvest strategy were relatively minor.

Discussion

This study presents a simple evaluation of how harvest control rules under a regime with lower mean recruitment will likely result in an increased likelihood that the stock will decline and that fishery production will decrease. This type of evaluation provides a quick way to evaluate critical environmental conditions against alternative tactical harvest policies. We provide a suite of indicators for stakeholders to consider, following the approach applied in southern bluefin tuna (Kurota *et al.*, 2010), and provide an integrated approach for combining indicators such that weights can be elicited by stakeholder involvement (Lane and Stephenson, 1998; Perry *et al.*, 2010). This integrated approach to applying weights to performance indicators could be developed as part of a full-decision theoretical approach to risk aversion, such as that presented by Thompson (1999).

In this study, the evaluations ignored the impact of generating new data from an operating model and conducting a full feedback loop where data were simulated from each year and assessment models were rerun (Smith, 1994; Fulton *et al.*, 2007; A'mar *et al.*, 2008). However, for the purposes of evaluating the impact of possible future recruitment scenarios under different harvest scenarios, the projection model approach provides insight on trade-offs of the different approaches without the added complexity of how the assessment process may or may not introduce long-term biases. The approach presented here makes several simplifying assumptions, including the assumption that pollock production is primarily driven by bottom-up forces that can be appropriately indexed by summer temperature. There are many examples where control mechanisms that were identified in one regime may no longer apply when it changes (Hollowed *et al.*, 2009). To caution against the use of a spurious relationship, we conducted a careful analysis of the data before use in the stock projection (Mueter *et al.*, 2011). We also note that mechanistic and realistic models that are more complex are under development and that these models provide support for the mechanism used in this analysis. However, given the uncertainty in our current knowledge of complex ecosystem dynamics, there is no guarantee that increased model complexity will result in predictions that are more accurate (Adkison, 2009; Stow *et al.*, 2009). The example presented here should be viewed as a first approximation of climate change effects on the pollock fishery.

The process used to select harvest strategies could be improved considerably. Our approach relied heavily on the professional judgement of the authors and qualitative information from interviews. A more comprehensive approach would be to develop worldwide models of fish markets (Mullon *et al.*, 2009), though it should be noted that significant uncertainty is likely to persist in these markets and models. Merino *et al.* (2010) extended their evaluation of global market conditions to account for climate change impacts on small pelagic fisheries and fishmeal. Dichmont *et al.* (2008) evaluated the economic impacts of trawling on the benthos. Their approach could be adapted to the current study by accounting for the extent of fishing effort required to catch the TAC in simulations. However, this would require a means to incorporate the impact of fuel prices on the performance of different fishing sectors.

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